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CARBON FIBRE REINFORCED PLASTIC COMPONENTS FOR AEROSPACE USE

M. W. Jones

Imperial Metal Industries Ltd.
Kidderminster, England

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Summary

Royal Aircraft Establishment

An outline is given of the development history of (RAE) carbon fibre reinforced plastics.

Initially, development was inhibited by poor interlaminar shear strength. However, composite properties have improved since the advent of various surface treatments derived by the fibre producers.

Present work indicates certain criteria by which resins are selected for use as a matrix with the two available types of RAE fibre. These are more critical for filament wound cylindrical components than for pressed flat laminates, as shown by levels of fibre compaction achieved on hoop wound NOL rings and helically wound tubes.

Currently ~~At present~~, the strength data fall well below that available if the full strength of the single fibre or bundle is utilised. However, the majority of the fibre stiffness has been achieved in unidirectional composites.

Illustrations are shown of a carbon fibre reinforced plastic and honeycomb sandwich satellite structure which has been constructed to investigate the efficacy of methods selected for laminating polygonal cylindrical shapes, the subsequent adhesive bonding and the final machining to complete the structural assembly.

* Head, Hardware Techniques Group, Summerfield Research Station (an agency establishment of the Ministry of Technology).

Introduction

The development at the Royal Aircraft Establishment, Farnborough, of high modulus carbon fibre started during 1963 based on the poly-acrylonitrile fibre. The advances made were published in 1966 by Watt, Phillips and Johnson (1). Two types of fibre are now in production at several sources in the United Kingdom under licence from N.R.D.C. Type 1 (High Modulus) is a material with a very high tensile modulus (60×10^6 psi) and Type 2 (High Strength) has a lower modulus (40×10^6 psi) but has a very high strength (400 000 psi) compared with type 1 (250 000 psi). The fibres are compared with other fibres on a specific basis in Figure 1.

The fibre properties have been discussed in great detail elsewhere (2). Early work on unidirectional composites indicated extremely attractive properties might be achieved, but the low interlaminar shear strength of the fibres was a limiting factor.

Several surface treatments have been developed, which have the effect of improving the interlaminar shear strength of Type 1 fibre from between 2 500 and 4 000 psi to over 8 000 psi; and Type 2 fibre from 5 000 to 7 000 psi upto over 11 000 psi.

This paper outlines the present status of ~~the~~ high modulus carbon fibre and presents composite properties obtained using fibres treated to give higher interlaminar shear strength. This increase in fibre performance has resulted in the necessity for changes in composite fabrication techniques compared with those used with glass fibre. The effect is demonstrated by results obtained from both flat pressed laminates and filament wound NOL rings and cylinders.

Fabrication of complex structures has been investigated using a prototype satellite structure. The paper discusses the selection of techniques for the fabrication of thin walled polygonal cylinders and the subsequent assembly together with panels of aluminium honeycomb core. Mention is made of machining methods employed to reach the final shape.

Finally, an indication is given of areas in the aerospace field where the fibre has potential for improved system efficiency.

Status of Carbon Fibre Reinforced Plastics

Both types of fibre are produced as tows containing 10 000 filaments of approximately 0.0003 in diameter in 1 000 ft, 40 in and 1 in nominal lengths. Lengths of 10 000 ft may be available in 1970.

The fibres are normally surface treated to give the improved interlaminar shear strengths. The fibre manufacturers claim that fibre strength and modulus are not impaired by their standard surface treatments.

The effect of surface treatment on composite properties is shown in Table 1 by the change in flexural strength and modulus of unidirectional flat bars made using Epikote 828/MNA/BDMA resin.

Tows can be impregnated with a solvent based resin to give 1-2% by weight of resin to improve handleability and to promote surface wetting. These tows can be used for wet laying-up or pre-impregnation to give a higher resin content.

Various compression moulding techniques have been examined for compaction efficiency linked with minimum void content. Shaped beams and flat bars with fibre contents upto 65% by volume have been made by the leaky mould technique (3) using steel or aluminium tools. Flat plates with orthogonal fibre directions have been press moulded between heated platens. Excessive moulding pressure inhibits resin flow and gas expulsion if applied too soon in the press cycle after the period at contact pressure, and acceptable thin laminates are formed at a moulding pressure of 50 psi with pre-impregnated type 1 fibre and epoxy novalac unidirectional sheet. From this work, an autoclave cycle of 2 hours at 75 psi and 165°C was selected for polygonal cylinders. This process gave satisfactory components with a fibre content of 50% by volume.

Filament winding of continuous roving is still in the infancy stage. Sufficient work has been done, however, to give indications of suitable manufacturing processes.

All methods of manufacture and assembly for adhesive bonding must take accounts of the large difference in the coefficient of thermal expansion between the fibre and metals which are used for mandrels, such as steel and aluminium. A unidirectional polyester composite, reinforced with 40% of type 1 fibre by volume, gave $-0.73 \times 10^{-6}\ {}^{\circ}C^{-1}$ as a typical figure (3).

Influence of Resin Properties on Composite Performance

The composite properties in Table 1 indicate that performance may be limited by the choice of Epikote 828/MNA/BDMA as the matrix system. Some of the properties of this resin system are set down in Table 2 in comparison with a resin system ERLA 4617/mPDA, which has been specifically developed by Union Carbide for use with high modulus fibres. The resulting change in interlaminar shear strength is demonstrated in Table 3. With type 1 fibre, there is little difference, but the interlaminar shear strength is nearly doubled by use of ERLA 4617/mPDA with type 2 fibre.

The effect of the increased modulus and elongation to break of the matrix is to retard the initiation of cracks, emanating from stress concentrations at the interface or elsewhere, which rapidly propagate through the composite including the fibres. The data in Table 4 show that the viscosity of the resin and the fibre modulus effect the level of compaction achieved in wet wound NOL rings produced under similar conditions.

The reduction of viscosity increases the ability of the resin to cover the surface of each fibre without entrapping air. Also the escape of entrapped air or solvent remaining after fibre pre-impregnation or products of cure are inhibited by matrix viscosity and fibre modulus. This is much more important for filament winding than for compression moulding.

Table 4 also shows that the stiffness of the NOL ring, as measured by diametral deformation modulus, is such that the majority of that available from the fibre is obtained. However, the tensile strength is only half way to using the whole fibre strength. It is likely that the results obtained from Type 2 with ERLA 4617/mPDA were inhibited by the presence of an epoxy sizing of the fibre surface.

Several other resin systems have been tried with varying degrees of success in particular composite configurations. No single system has been found which will satisfy all manufacturing and structural requirements. Hence, it is envisaged that a whole family of carbon fibre reinforced plastics will emerge from the development phase.

Utilisation of Carbon Fibre In Prototype Structures

Pressure containers

The work on pressure vessels has been limited by the availability of continuous fibre. Early deliveries have been used for winding dome ended bottles and test cylinders. The 6 in diameter bottle has been selected as the standard development vehicle (Figure 2). In view of the added complications of mandrel construction, however, 3 in diameter cylinders have also been helically wound at 55^{o} on an aluminium mandrel to evaluate the relevance of the previous work to filament winding. The unlined tubes were pressure tested in the hoop direction only, the longitudinal loads being carried by an internal dumbell. The results obtained from the tubes are contained in Table 5.

All tubes burst in hoop and were not porous upto burst pressure. The fibre stresses achieved were of the same order as those obtained from NOL rings. Compaction can probably be improved by increasing winding tension and reducing the number of filaments in the bundle or by using flattened pre-impregnated roving.

Satellite structure

A carbon fibre, reinforced plastic satellite structure has been designed and built as a vehicle for fabrication development and to provide a comparison with conventional metal structures.

The modular principle of construction is demonstrated in Figure 3. All loading points, such as solar cell array mountings, are directly linked. Four octagonal spines form the main structural members; composite panels are formed by sandwiching aluminium honeycomb core between carbon reinforced plastic cylindrical shapes of various cross-sections such as squares, rectangles and triangles. The optimum design indicates a weight saving of 38% of the equivalent metal structure.

Pre-impregnated sheet, 0.010 in thick, containing Type 1 treated fibre and epoxy novalac resin 50% by weight, was chosen for fabrication because of availability. Each cylindrical shape is made up of single orthogonal layers. The bending rigidity of the panel, measured by five point bend test, was 29.4×10^{3} lb/in^{2} for a mass per surface area of 0.6 lb/ft^{2} and section depth 0.43 in.

The cylindrical sections were made by hand laying up the pre-impregnated sheet onto aluminium mandrels which were covered by a parting agent sheet, bleeder cloth and rubber sleeve and then the assembly was autoclaved at 70-80 psi and 165°C for two hours prior to post cure at 170°C. The process was chosen as a result of compaction trials, which indicated that high pressure moulding without a low pressure phase trapped voids in the laminate and inhibited compaction. Optimum thin laminate moulding conditions are in the region of 50-70 psi for this material combination.

The assembly was bonded together with BSL 308 available from Bonded Structures Division of C.I.B.A. (A.R.L.) Ltd. This material requires a cure temperature of 165-170°C. As a result of the thermal gradients across the panel and the large difference in thermal expansion rates, the whole assembly was bonded together in one cycle. A short section of the bonded structure is shown in Figure 4 with the outer panels cut away on three sides. The full bonding assembly is shown in Figure 5.

Machining conditions are dictated by the necessity for material to be removed with the minimum energy to limit crack propagation due to brittle fracture, especially in thin sections. In-plane edge grinding was chosen for the finish machining of the end faces (Figure 6) and also the cut-outs, which can be seen in the completed structure in Figure 7.

Future Direction

Glass reinforced plastic rocket motor cases have been successfully used on various space launcher systems. In order that maximum advantage can be taken of the fibre strength, the vessels must be lined because of resin crazing, which occurs halfway to failure of the fibre. The initial tube tests indicate that no lining will be necessary with CFRP components made with type 1 fibre, which have to retain hydraulic pressure. Further, by inference, no resin crazing has occurred. In view of this CFRP motor cases should be able to withstand more rigorous moisture conditions. Furthermore, strain limitations due to propellant properties will not limit the exploitation of fibre strength. The compaction levels must be increased, however, and the utilisation of fibre strength improved.

On the basis of the tests carried out on CFRP and aluminium honeycomb core sandwiches, this form of construction should prove to be attractive for substitution for existing aluminium sandwich panels, such as trailing edges and

control surfaces, as well as satellite structural components.

The work on blade development has been described elsewhere (2,5).

Other uses in the aerospace field await further development.

In conclusion, carbon fibre reinforced plastics must still be considered to be in the development phase. However, the current pace of development in the United Kingdom suggests that a considerable amount of prototype development data will be available by the start of 1970, which will enable engineers to place the material in a real comparative position with other materials.

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TABLE 1

Effect of Fibre Treatment on Composite Properties

Fibre Type	Interlaminar Shear Strength (quoted) psi	Unidirectional Composite Flexure Strength psi	Unidirectional Composite Flexure Modulus psi	Fibre Content % Volume
1. Untreated	2500-4000	70,000-83,000	20×10^6	63
2. Untreated	5000-7000	190,000-214,000	17×10^6	71
1. Treated	over 8000	145,000	29×10^6	60
2. Treated	over 11000	220,000	20×10^6	67

Resin Epikote 828/MNA/BDMA

TABLE 2

Typical Resin Properties

Resin	828/MNA/BDMA	ERLA 4617/m-PDA
Tensile Modulus psi	430,000	783,000
Tensile Strength psi	11,000	19,200
Elongation %	2 - 3	7.5
Compression Modulus psi	345,000	890,000
Typical Cure Cycle	3 hrs. @ 150°C	4hr. @ 85°C, 3hr. @ 120°C 16 hr. @ 160°C
Viscosity @ 25°C poise	25	0.86

Table 3. Effect of Resin Type On Interlaminar Shear Strength.

Notes: Fibres treated but not sized.
Fibre Content by Volume - Approximately 50%.
NOL Ring Short Beam Test.

Fibre Type	Resin	Interlaminar Shear Strength (psi).
1	ERLA4617/mPDA	6100 - 8000
2	ERLA4617/mPDA	12000 - 12300
1	828/MNA/BDMA	7700
2	828/MNA/BDMA	6800 - 7900

Table 4. Effect of Resin and Fibre on NOL Ring Properties

Fibre treated and epoxy sized

Rings wound at 80°C.

Fibre Type	Resin	Carbon % Volume	Diametral Deformation Modulus psi	Composite Tensile Strength psi
2	828/MNA/BDMA	40	14.7×10^6	84000
2	ERLA 4617/mPDA	58	14.6×10^6	109000
1	ERLA 4617/mPDA	37	20.6×10^6	84000

Table 5. 3 in Diameter Tube Design

Type 1 treated and epoxy sized fibre
55^{o} angle of wind

Resin	Fibre Content by volume %	Hoop Burst level psi	Thickness in	Fibre Stress psi
828/MNA/BDMA	31	2800	0.107	184000
ERLA 4617/mPDA	35*	3000	0.093	193000

* Note: compares with 37% for NOL ring

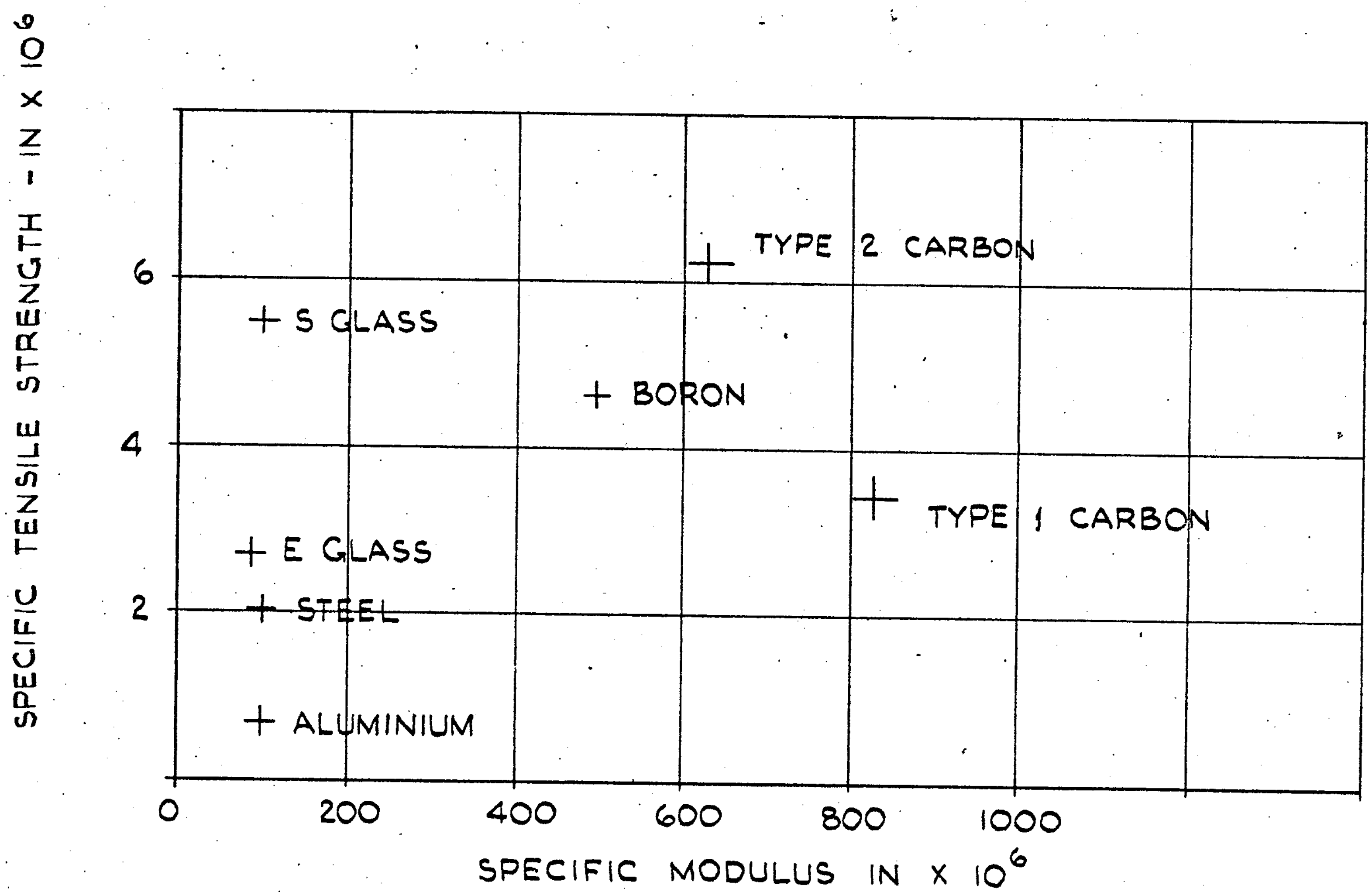


FIG. 1. SPECIFIC PROPERTIES.

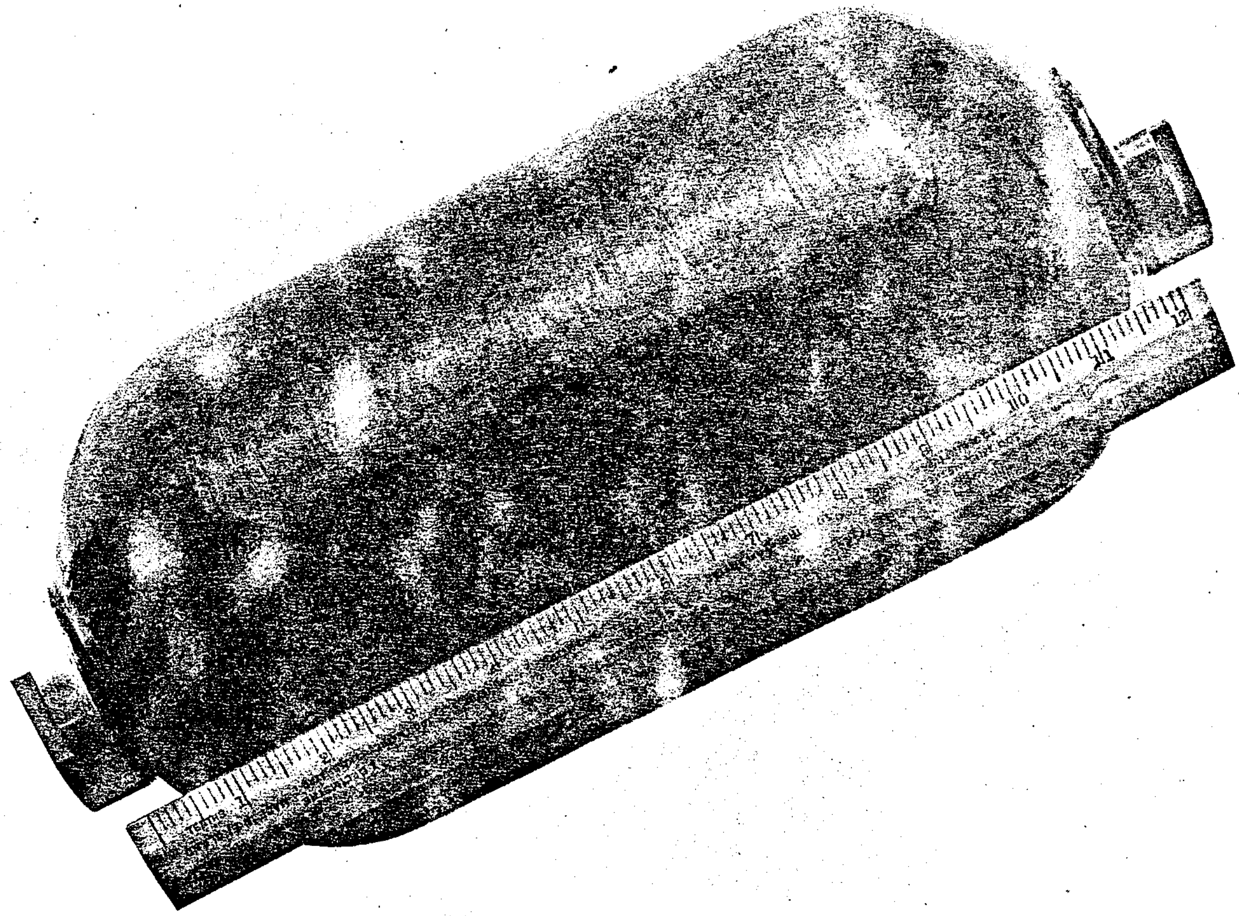
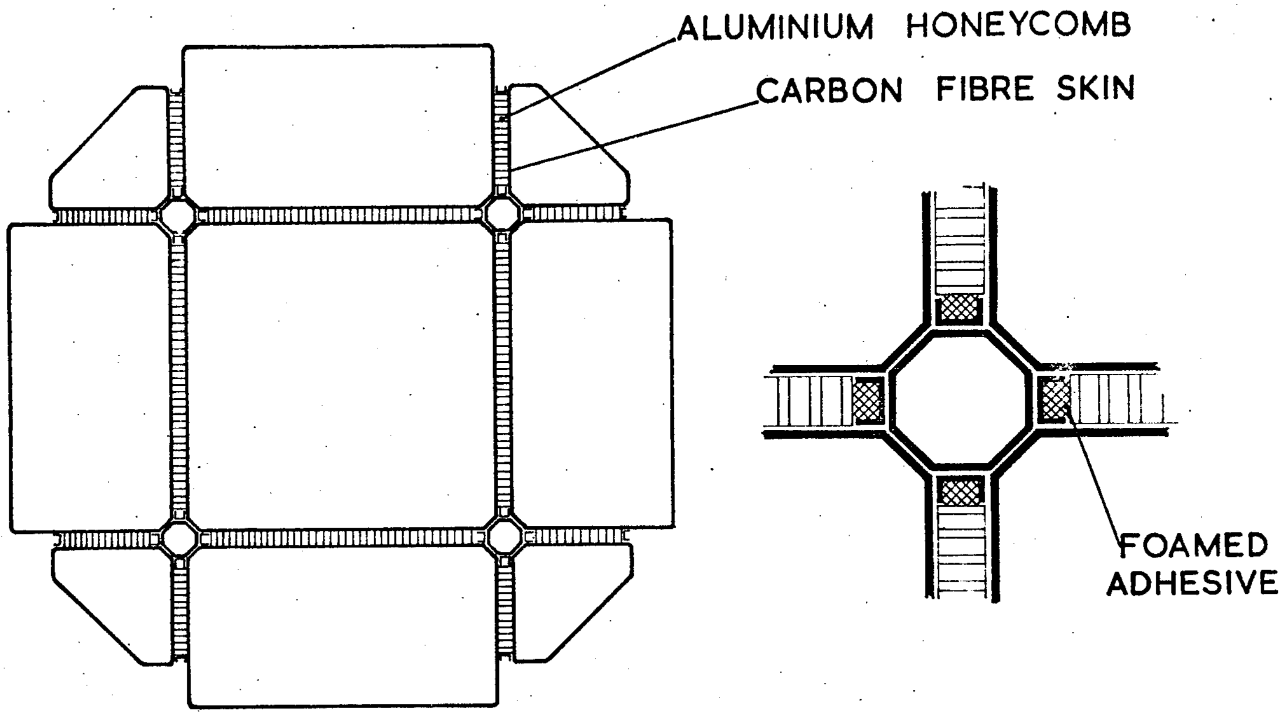


Fig. 2 - 6 inch diameter pressure vessel



SATELLITE STRUCTURE

Fig.3 - Diagram of cross section of satellite structure.

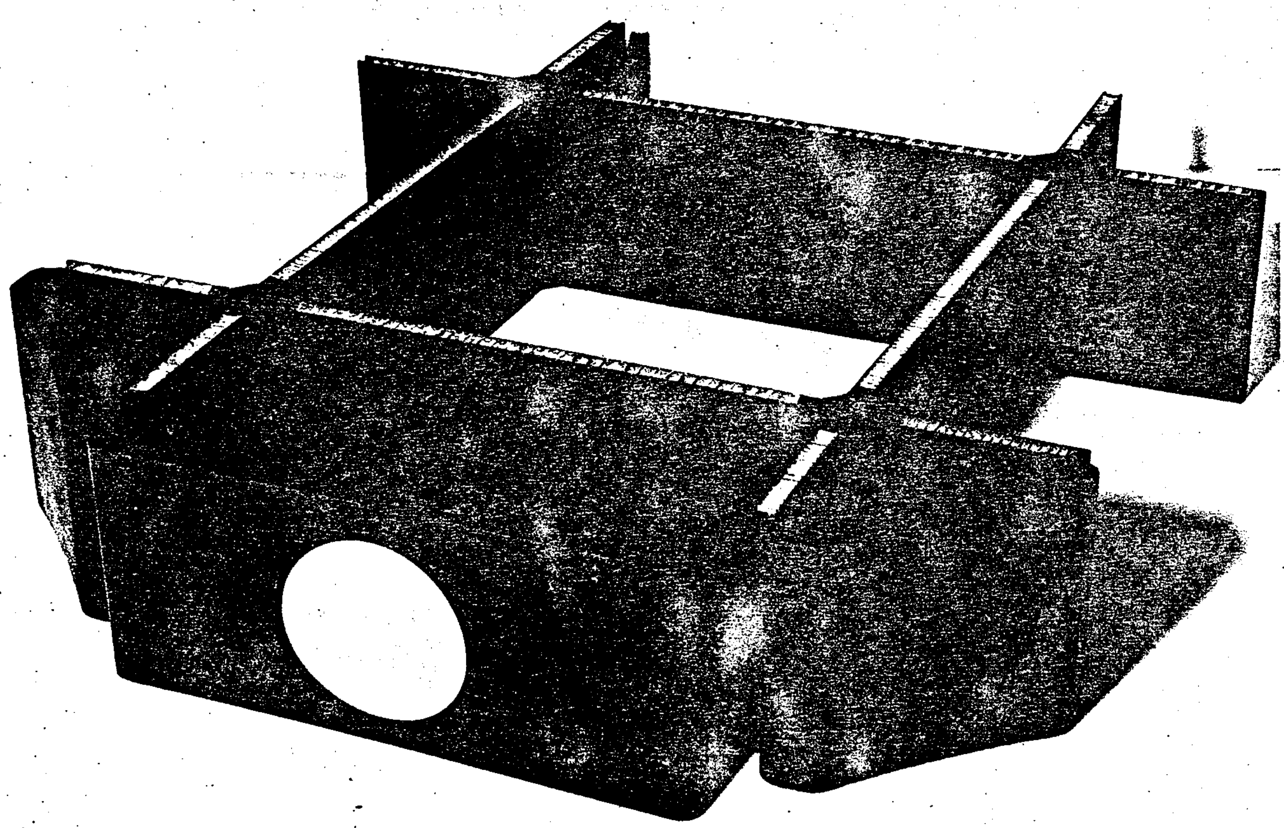


Fig.4 - Model Section of satellite structure.

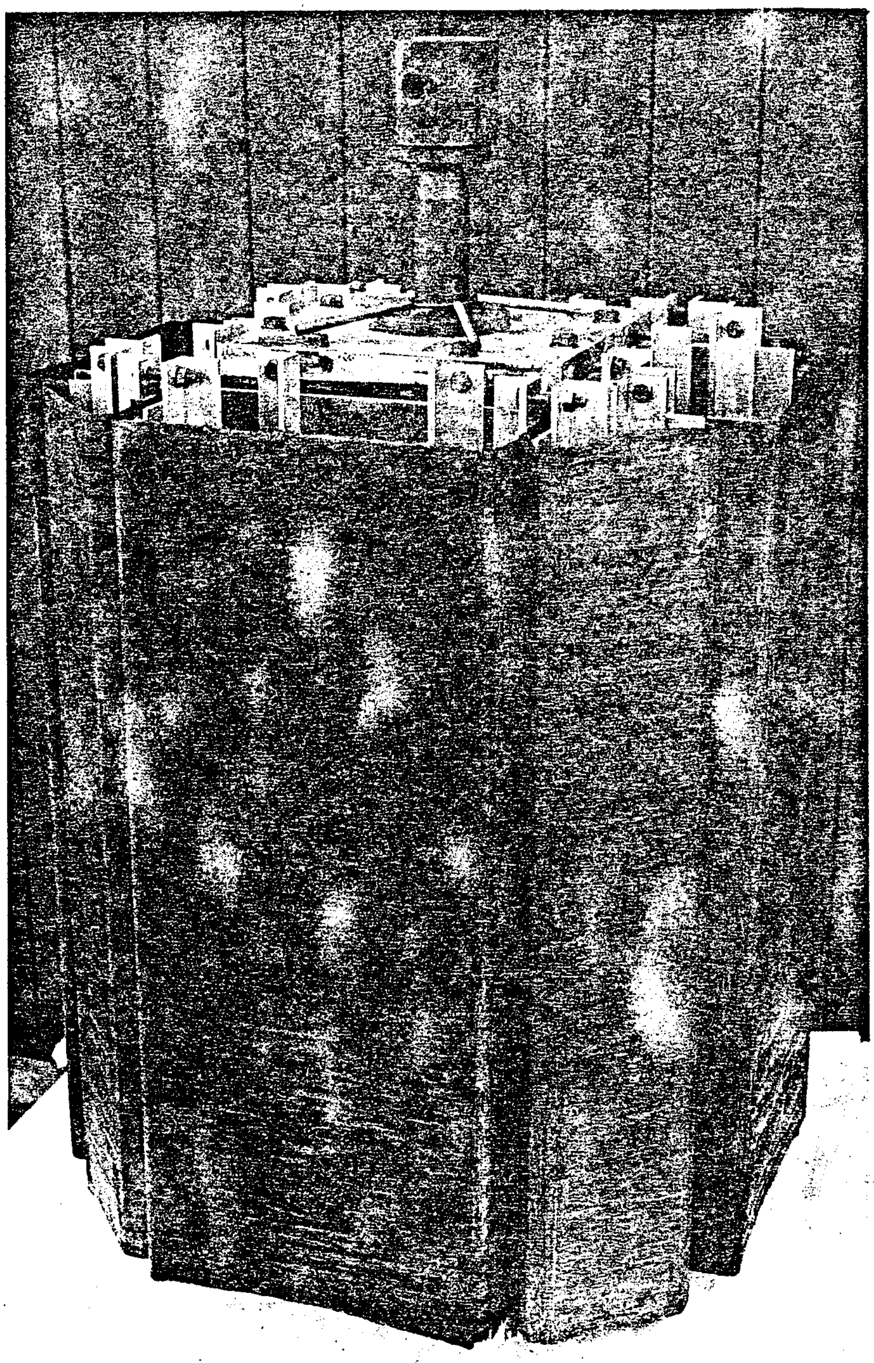


Fig.5 - Adhesive bonding assembly of
the satellite structure.

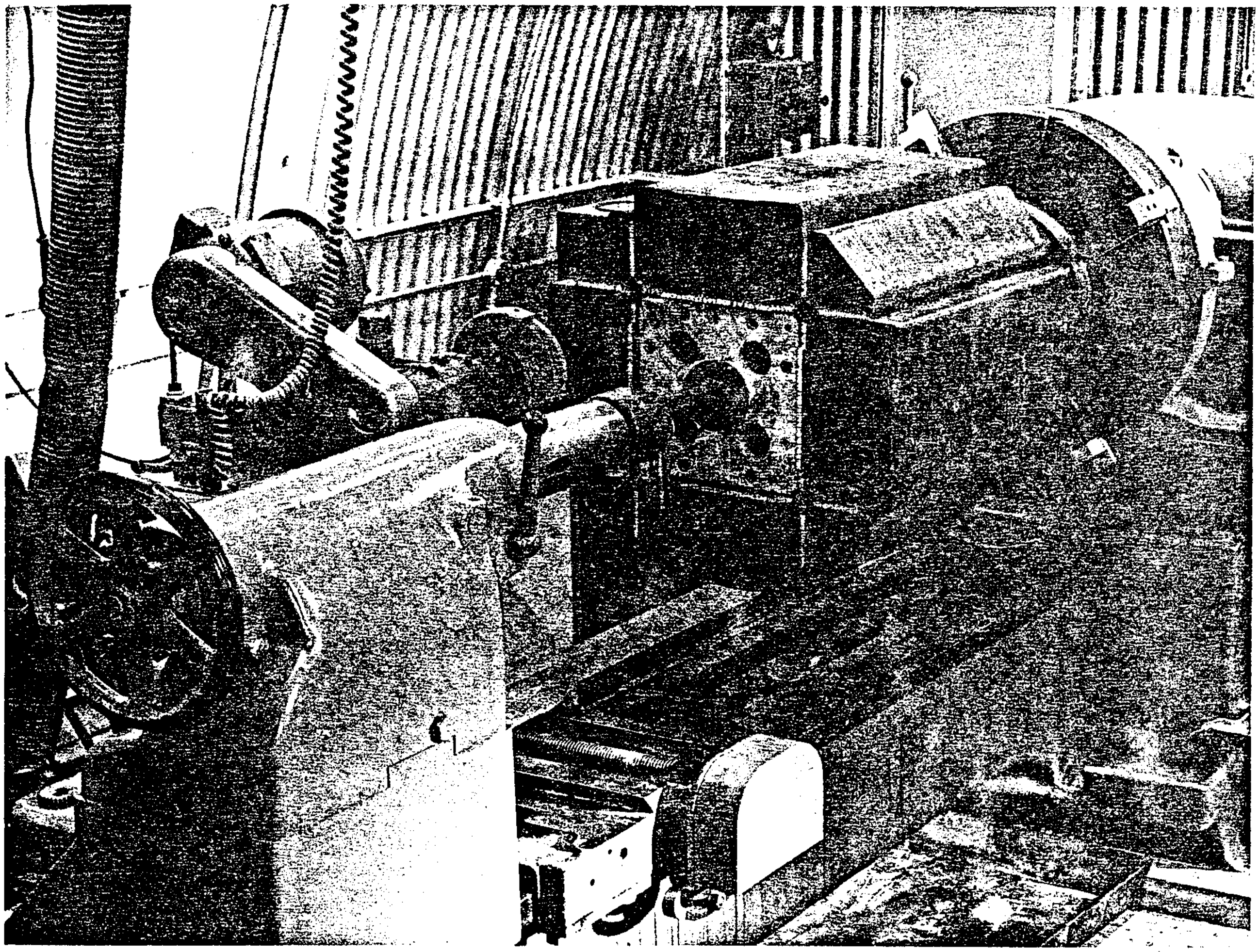


Fig.6 - Machining the end face of the
satellite structure.

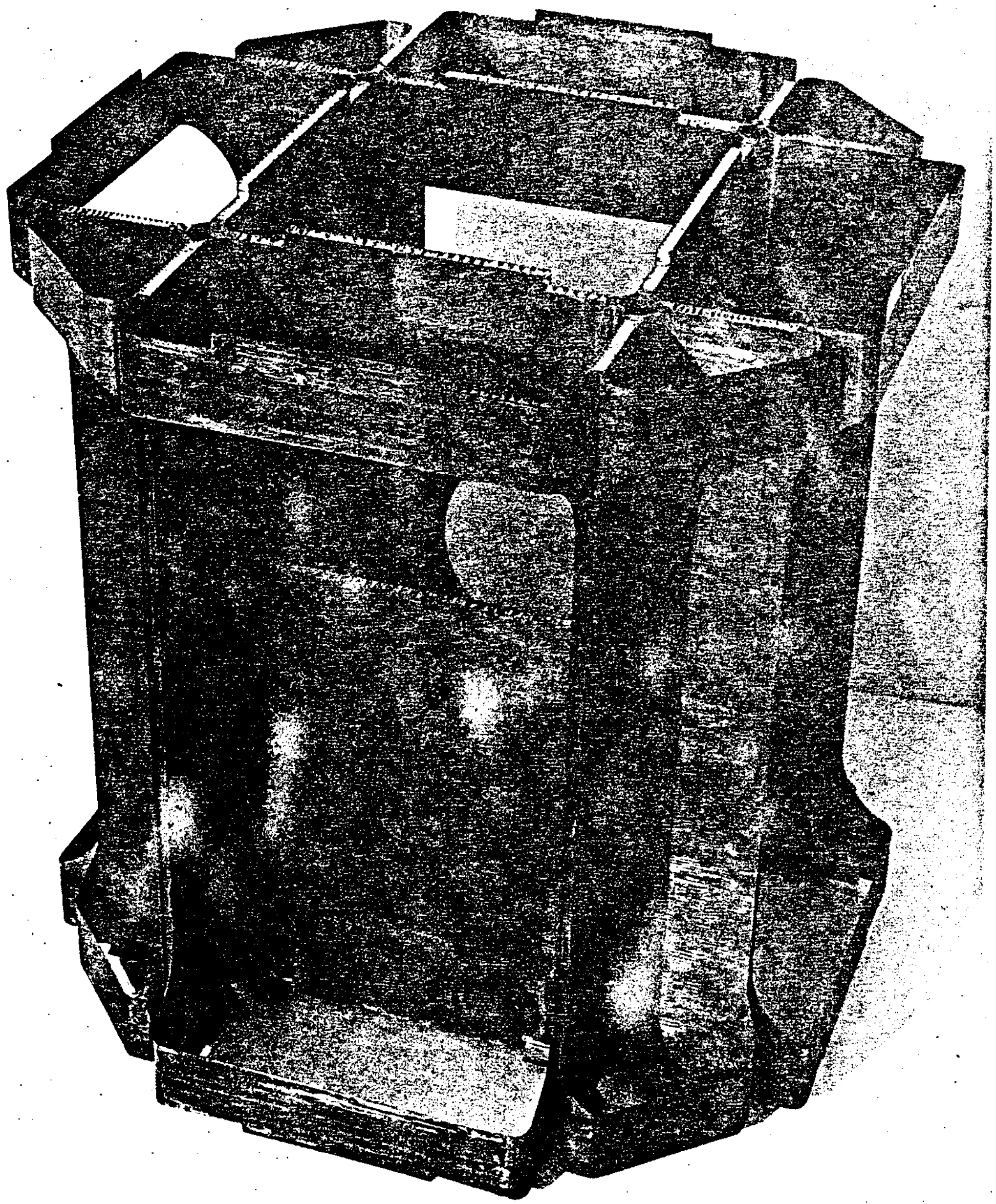


Fig.7 - Finish machined satellite structure.